FINAL REPORT
National Institute of Standards and Technology
Measurement, Science and Engineering
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Contract No.: 60NANB7D6166
Title: Atomically-resolved electronic structure of epitaxial graphene
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Institution: Georgia Institute of Technology
NIST Technical Contact: Joseph A. Stroscio
Report Period Start: 15-Aug-2007
Report Period End: 15-Aug-2008
Report Date: January 12, 2009

Report Period 1 Activities: 15-Aug-2007 to 30-Sep-2007

During the report period, previously-collected data was analyzed thoroughly, resulting in the submission of two publications, and new experiments on graphene defects were carried out using room-temperature scanning tunneling microscopy. This resulted in a third manuscript submitted for publication.

In preparation for new experiments, the NIST-CNST low-temperature scanning tunneling microscope system was modified slightly, and methods of sample preparation were developed. Mr. Greg Rutter made one trip to Georgia Tech in order to learn the technique of hydrogen-etching silicon carbide substrates.

Budget expenditures for the report period covered travel, tuition, and salary for Mr. Rutter.

Report Period 2 Activities: 01-Oct-2007 to 30-Mar-2008

Modifications of the the NIST-CNST low-temperature scanning tunneling microscope system were completed successfully, after some protracted challenges. Data analysis of epitaxial graphene continued, with results pointing toward new experimental directions. It was shown that measurements of the difference in STM-imaged surface height between the two sublattice atoms of graphene provides a quantitative measure of the graphene interlayer coupling. An extension of this method could be used to map subsurface variations in electronic structure. Initial research into methods for passivating the SiC interface were undertaken, and hydrogen passivation was demonstrated for the bare surface. The temperature required for this process indicated that the surface adatoms are predominantly silicon, although the subsurface region is believed to be carbon-rich.

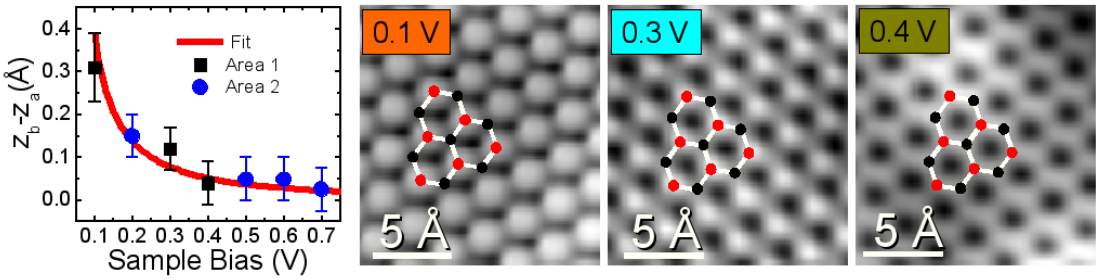

Fig. 1: Tunnel bias dependence of $(z_b - z_a)$, the difference in imaged height between the two graphene sublattice atoms (see red and black dots). Red curve in the plot is a model fit, from which the interlayer interaction strength is determined.

Experiments were initiated on a "conventional" 2D electron gas system: InAs surface-doped by manganese-atom adsorbates. A novel tip-induced switching of the Mn adsorption configuration was discovered. These reproducible events are still under study. It was also found that the distribution of Mn adsorbates creates a potential landscape that may be responsible for confinement of electrons when a magnetic field is applied. An unexpected splitting of the magnetic-field induced Landau levels was observed, which still requires explanation.

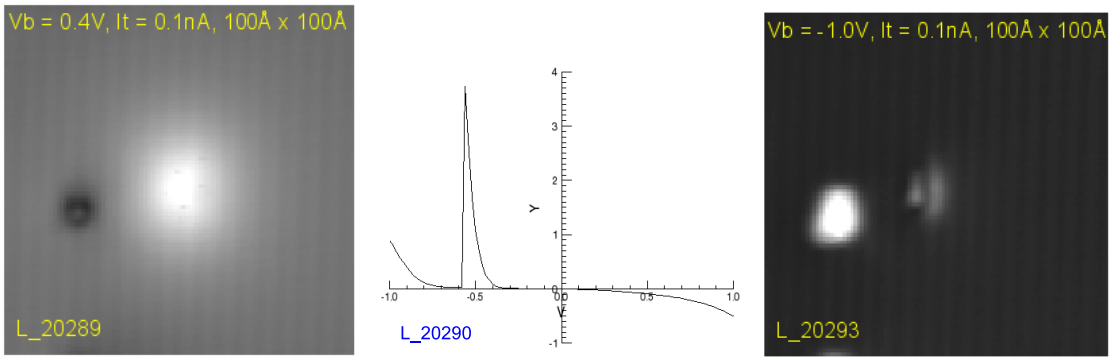

Fig. 2: Tip-induced configurational changes of Mn adsorbate atoms. Left image: Before tip-induced switch. Middle plot: Current versus voltage plot showing the switching event. Right image: After tip-induced switch.

Budget expenditures for the report period covered travel for Rutter and First, and tuition plus salary for Mr. Rutter.

The results of this work were partly responsible for securing a 3-year grant through the Nanoelectronics Research Initiative (NRI) for continuation of this collaborative research.

Report Period 3 Activities: 01-Apr-2008 to 15-Aug-2008

Atomic manipulation of CO on the Cu(111) surface was demonstrated, with testing and development of autonomous atom assembler software.

New measurements were undertaken on a sample of multilayer epitaxial graphene (MEG) grown on SiC(000$\bar{1}$) by the de Heer group at Georgia Tech. Scanning tunneling spectroscopy was

performed on this sample in magnetic fields up to 8 T. Surprisingly, the spectra show extremely sharp Landau-level peaks whose positions are correctly predicted by the theory of *single layer* graphene. The apparent decoupling of graphene layers in MEG is due to rotations between successive graphene layers. These are visible in the scanning tunneling microscope as Moiré-type superlattice periodicity modulating the atomic surface corrugation. The multilayer samples are found to be remarkably flat (under 20 pm peak-to-peak height modulation in the superperiod), relatively free of point defects (density $\approx 10^{10}\,\mathrm{cm}^{-2}$) and atomically continuous across rotational phase boundaries.

Budget expenditures for the report period covered travel for Rutter and First, and tuition plus salary for Mr. Rutter.

This work led to the Ph.D. Thesis and successful Thesis Defense of Dr. Rutter, and his winning the prestigious Dorothy M. and Earl S. Hoffman Student Award of the AVS.

Fig. 3: *Left:* Gregory Rutter receiving the Dorothy M. and Earl S. Hoffman award of the AVS from John Russell, Jr., President of the AVS. *Right:* Gregory Rutter (center) with graduate adviser, Phillip First (right) and CNST collaborator Joseph Stroscio (left).

Presentations

1. "Probing the Interface between Graphene and SiC at the Atomic-scale," N. P. Guisinger, G. M. Rutter, J. N. Crain, E. A. A. Jarvis, M. D. Stiles, P. N. First, and J. A. Stroscio, 54th AVS International Symposium, Seattle, WA, Oct. 16, 2007.

2. "Quasiparticle Interference in Epitaxial Graphene," G. M. Rutter, J. N. Crain, N. P. Guisinger, P. N. First, and J. A. Stroscio, 54th AVS International Symposium, Seattle, WA, Oct. 16, 2007.

3. "Investigation of Acceptor States and Landau Levels in (In,Mn)As by Scanning Tunneling Spectroscopy," Y. J. Song, N. Zhitenev, J. A. Stroscio, G. M. Rutter, and P. N. First, 2008 APS March Meeting, New Orleans, LA, March 10, 2008.

4. "Exposure of Epitaxial Graphene on SiC(0001) to Atomic Hydrogen," N. P. Guisinger, G. M. Rutter, J. N. Crain, P. N. First, and J. A. Stroscio, 2008 APS March Meeting, New Orleans, LA, March 11, 2008.

5. “Structural and Electronic Properties of Bilayer Epitaxial Graphene,” G. M. Rutter, P. N. First, J. N. Crain, and J. A. Stroscio, 2008 APS March Meeting, New Orleans, LA, March 12, 2008.

6. “Epitaxial Graphene: Layers of understanding (INVITED),” P. N. First, Aspen Center for Physics Graphene Workshop, Aspen, CO, June 17, 2008.

7. “Electronic properties of epitaxial graphene at the atomic scale,”G. M. Rutter (Nottingham Finalist), 2008 Physical Electronics Conference, University of California, Riverside, CA, June 22-25, 2008.

8. “Interface physics of epitaxial graphene (INVITED),” P. N. First, 2008 International Conference on Nanoscience + Technology (ICN+T 2008), Keystone, CO, July 23, 2008.

9. “Atomic Scale Properties of Epitaxial Graphene Grown on SiC,” G. M. Rutter, P. N. First, and J. A. Stroscio, AVS 55th International Symposium, Boston, MA, Oct. 20–24, 2008.

10. “Layer-dependent properties of epitaxial graphene on silicon carbide (INVITED),” P. N. First, AVS 55th International Symposium, Boston, MA, Oct. 19–24, 2008.

11. “Atomic Scale Investigation of Mn Impurities on the InAs(110) Surface,” Y. J. Song, G. M. Rutter, P. N. First, N. Zhitenev, J. A. Stroscio, AVS 55th International Symposium, Boston, MA, Oct. 19–24, 2008.

12. “Tunneling spectroscopies of epitaxial graphenes (INVITED),” P. N. First, ESF Graphene Week 2009, Obergugl, Austria, March 2–7, 2009.

Publications

Published:

1. G. M. Rutter, N. P. Guisinger, J. N. Crain, E. A. A. Jarvis, M. D. Stiles, T. Li, P. N. First, and J. A. Stroscio, *Imaging the interface of epitaxial graphene with silicon carbide via scanning tunneling microscopy,* Phys. Rev. B **76,** 235416 (2007).

2. N. P. Guisinger, G. M. Rutter, J. N. Crain, C. Heiliger, P. N. First, and J. A. Stroscio, *Atomic-scale investigation of graphene formation on 6H-SiC(0001),* J. Vac. Sci. Technol. A **26,** 932(2008).

3. G. M. Rutter, J. N. Crain, N. P. Guisinger, P. N. First, and J. A. Stroscio, *Structural and electronic properties of bilayer epitaxial graphene,* J. Vac. Sci. Technol. A **26,** 938(2008).

Submitted:

4. D. L. Miller, K. D. Kubista, G. M. Rutter, M. Ruan, W. A. de Heer, P. N. First, and J. A. Stroscio. *Magneto-oscillations and Landau quantization in decoupled epitaxial graphene multilayers*.